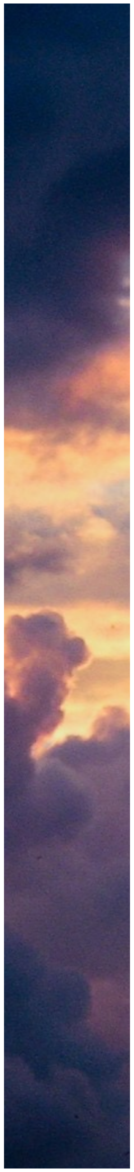

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Numerical study of sea-salt delivery to the clouds

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U.S. DEPARTMENT OF ENERGY BATTELLE

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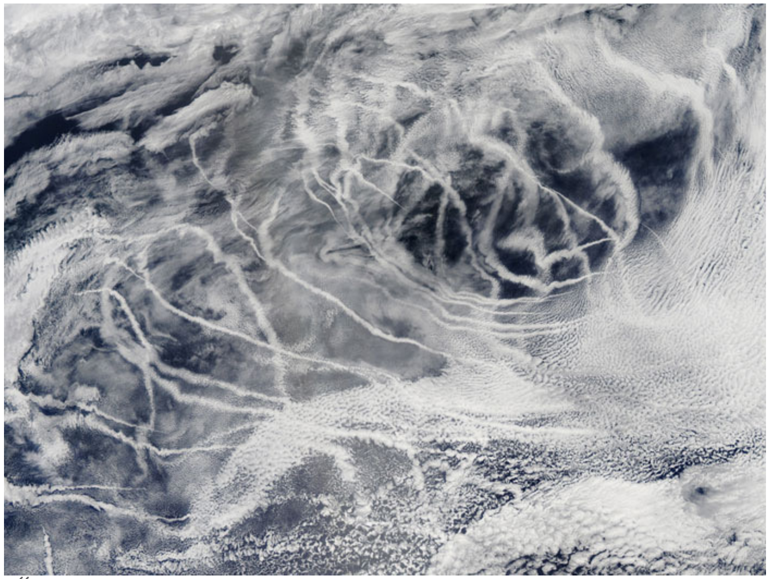
Motivation

- Marine Cloud Brightening (MCB) is a proposed technique to counter climate change
  - Increase the number of aerosol particles available to marine clouds to produce smaller cloud droplets
  - Smaller droplets:
    - Reflect sunlight more effectively
    - Inhibit the production of rain, tending to make clouds ”live” longer

- **Strategy:** Produce salt-water plumes near the ocean surface
  - Droplets evaporate to leave sea salt aerosol
  - Turbulent mixing is needed to loft the aerosol to cloud base

- Limited opportunities for controlled field experiments
  - Numerical Experiments
  - **How do clouds affect plume transport?**
  - **How do plumes affect cloud properties?**

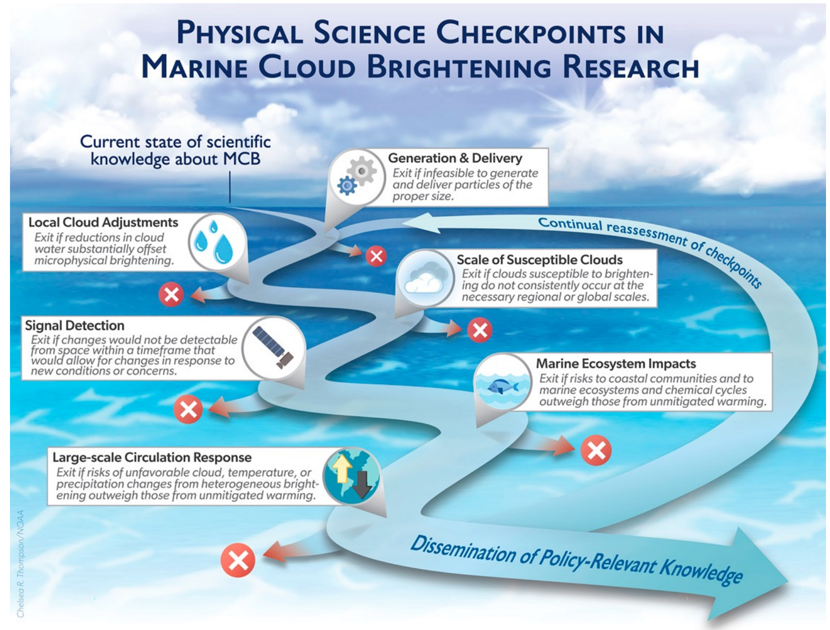


“Ship tracks” are brightened cloud areas that result from aerosol particles in ship exhaust. They are an inadvertent example of the same cloud responses MCB seeks to use. Credit: NASA/GSFC/Jeff Schmaltz/MODIS Land Rapid Response Team.

Objectives

- Numerical studies of saltwater droplet plumes emitted into stratocumulus-topped boundary layer
  - Large Eddy Simulations (LES)
  - Numerical sensitivity tests

- LES used for high resolution (10s of m) studies on smaller domains (10s of km)
- We focus on developing a **modeling framework** and analysis approach that allows us to assess the efficacy of different plume injection strategies
- PINACLES* - A novel, massively parallel LES code developed at PNNL for 3-D atmospheric turbulence, with focus on boundary layer and clouds

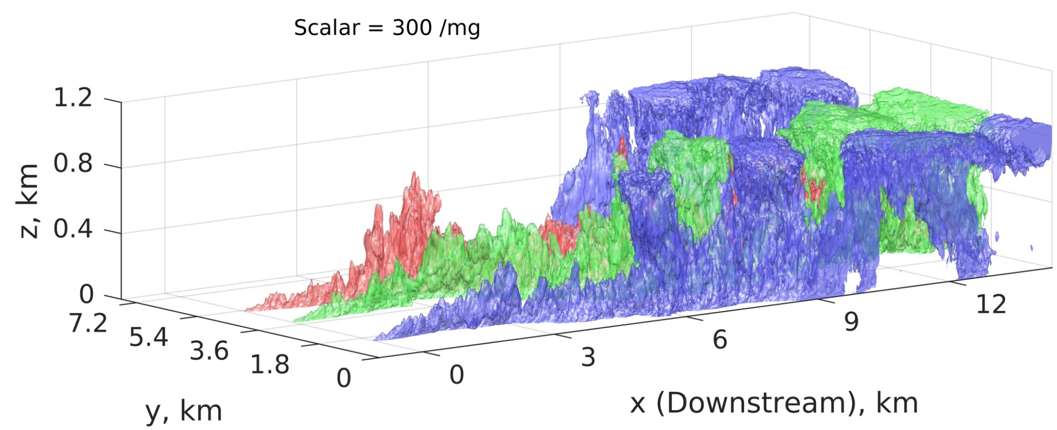


Marine Cloud Brightening research checkpoints
Image credit: Diamond et al., PNAS (2022)

*<u>**P**</u>redicting <u>**IN**</u>teractions of <u>**A**</u>erosol and <u>**C**</u>louds in <u>**L**</u>arge <u>**E**</u>ddy <u>**S**</u>imulation
Pressel & Sakaguchi, PNNL Technical Report (2021)

Numerical Method

- Stratocumulus cloud test case with mean wind oriented along the longest axis of the domain
- Simulation domain is 15 km x 7.5 km x 1.5 km, and simulations use 20 m x 20 m x 5 m grid-spacing => **over 84 million grid points**
- Two-moment bulk microphysics scheme[1]
  - **Linked to a bi-modal, two-moment prognostic treatment of aerosol[2]**
- Plumes injected just above the surface as volumetric source terms
- Similar simulations with identical grid spacing and initial conditions for **sensitivity studies**



Computational domain including plume visualization
Image credits: Peter Blossey

- Passive plumes (inert tracer) vs
  active plumes - aerosol (250 nm) in water droplets (1 mm) at 5 injection rates ($1e^{13} – 1e^{17}$ s^{-1})
- 2 major comparisons
  - How large of an area is perturbed?
  - How much brighter is the perturbed area?

[1] *Morrison et al., Journal of the Atmospheric Sciences (2005)*
[2] *Wyant et al., Journal of Advances in Modeling Earth Systems (2022)*

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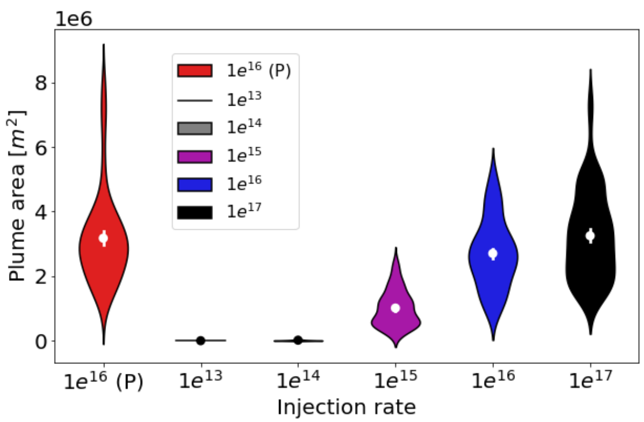
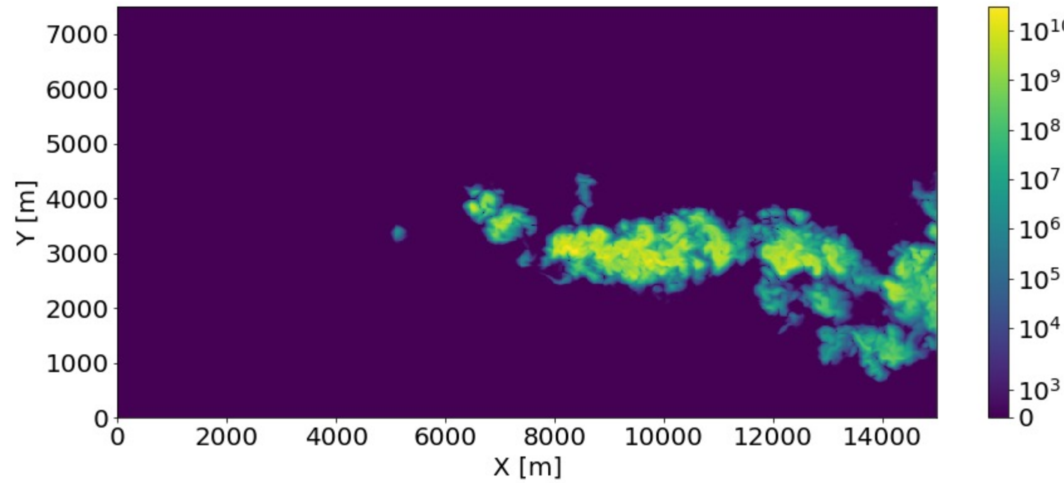
Results – Plume area

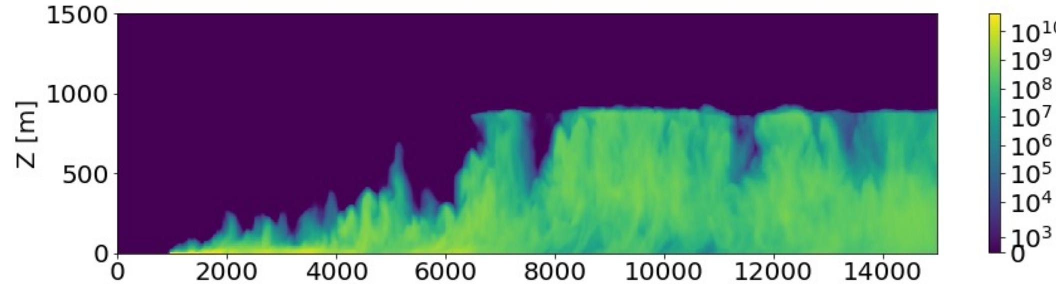
- Active plumes may loft less quickly due to negative buoyancy from droplet evaporation
- Plume area at 600 m increased with injection rate
- Active plume at 600 m have slightly smaller area than the corresponding passive plume



Plume area at 600 m calculated from simulations using passive (red) and active plumes with injection rates of 1e[13] (green), 1e[14] (gray), 1e[15] (magenta), 1e[16] (blue), and 1e[17] (black) s[-1]



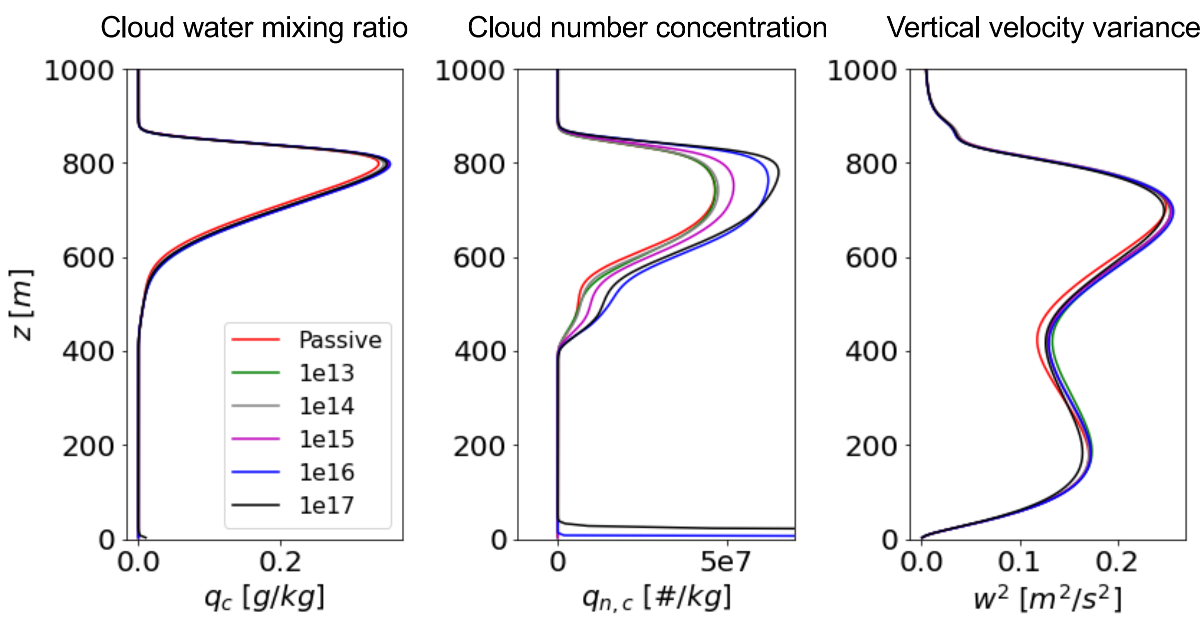
Plume tracer contours at z = 600 m from simulation using active plumes (blue)



Plume tracer contours (averaged across y) from simulation using active plumes (blue)

Results – Cloud properties

- No change in cloud water mass
- Droplet concentration increases with active plume injection rate (starting with 1e^{15} s^{-1})
- Active plumes result in smaller cloud droplets
- Little change in sub-cloud layer turbulence

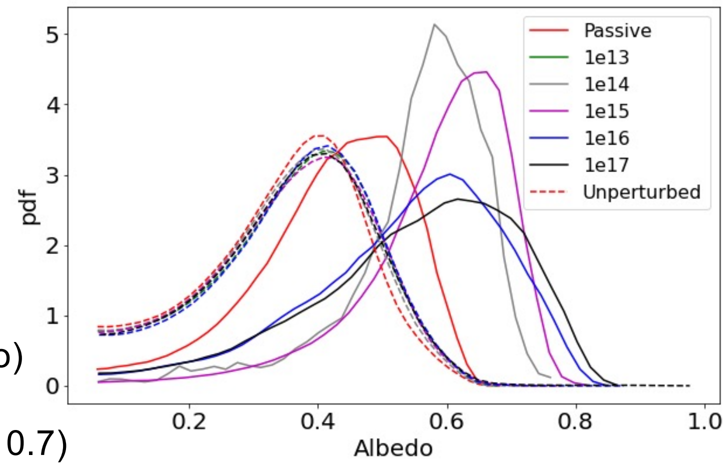


Mean vertical profiles calculated from simulations using passive (red) and active plumes with injection rates of 1e^{13} (green), 1e^{14} (gray), 1e^{15} (magenta), 1e^{16} (blue), and 1e^{17} (black) s^{-1}

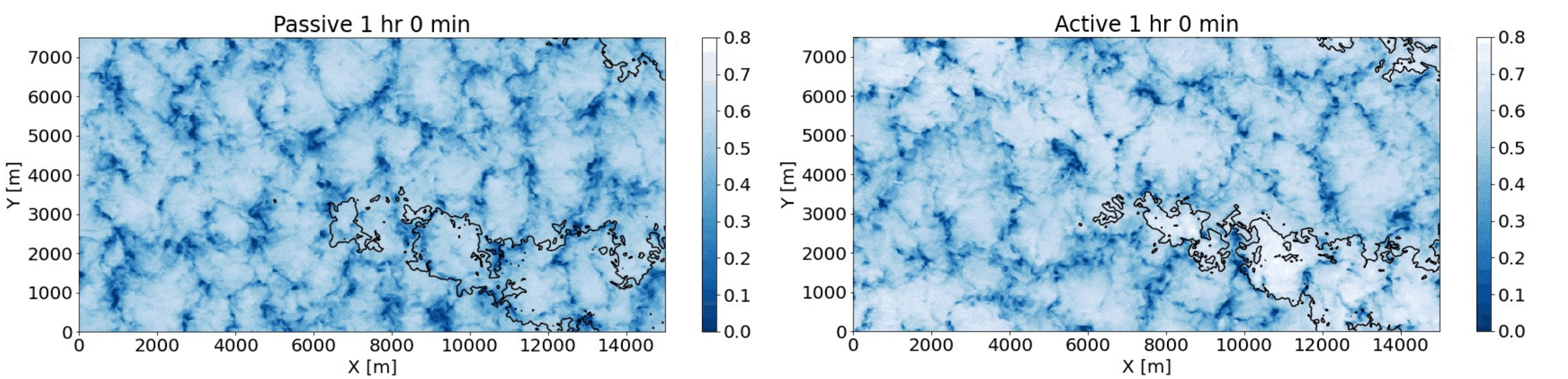
Results – Pseudo albedo

$$\alpha = \frac{(1-g)\frac{3}{2}\int \frac{q_c + q_r}{r_{eff}}\,dz}{2 + (1-g)\frac{3}{2}\int \frac{q_c + q_r}{r_{eff}}\,dz}$$

- Out of plume albedo peaks around 0.4
- Passive plumes loft to bright parts of the cloud (0.5 albedo)
- Active plumes increase the cloud brightness further (0.6 - 0.7)



Probability distribution function of pseudo albedo in-plume (solid) and out-of-plume (dashed) from simulations using passive (red) and active plumes with different injection rates



Pseudo albedo contours calculated from simulations using passive (left) and active (right) plumes ($1e^{16}$ s^{-1}), black curves correspond to where plume reaches threshold of 100 mg/kg

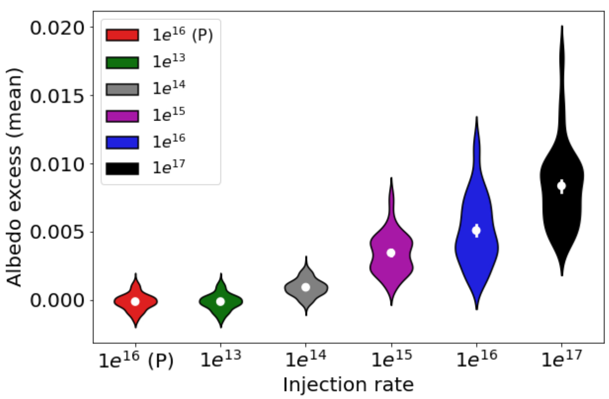
Conclusions

Other comparisons

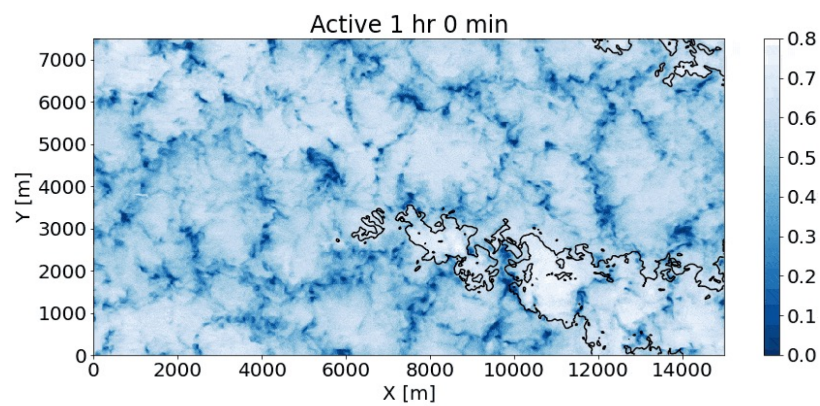
- Simulations with higher grid resolution
- Nested simulations vs Periodic domains
- Advection scheme sensitivity

Future Work

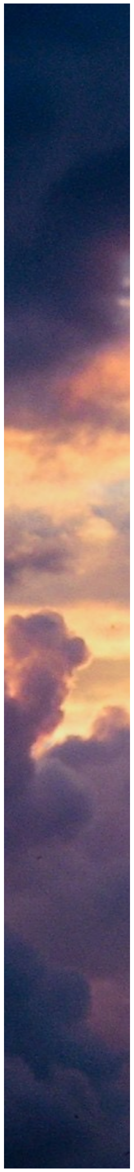
- Larger domain simulations
- More diverse cloud setups – precipitating, high LWP, etc



Average pseudo albedo excess calculated from simulations using passive (red) and active plumes with injection rates of $1e^{13}$ (green), $1e^{14}$ (gray), $1e^{15}$ (magenta), $1e^{16}$ (blue), and $1e^{17}$ (black) s^{-1}



Pseudo albedo contours calculated from simulations using active (blue) plumes, black curves correspond to where plume reaches threshold of 100 mg/kg



Thank you